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Abstract: A summary of results on synchrotron radiation is presented along with notes on its properties and applications. Quantum aspects are briefly mentioned. Synchrotron radiation facilities are described briefly with a detailed coverage to the accelerator programmes in India. The relocated and other upcoming synchrotrons are also described in some detail.

I. INTRODUCTION TO SYNCHROTRON RADIATION

Charged-particles when accelerated radiate electromagnetic energy. This interesting physical phenomenon, now known by the name *synchrotron radiation* had its theoretical beginnings a long time ago at the time of classical electrodynamics. At that time, only the very basic features of this physical phenomenon were studied and expressions were derived for several quantities such as the *total radiation intensity*, *spectral distribution* and *angular distribution* [1]. These theoretical studies had to wait for about half a century till the development of charged-particle accelerator technology for a direct observation and experimental verification. It was experimentally observed for the first time in 1947 in the $70 MeV$ electron synchrotron and hence the name *synchrotron radiation.* This observation generated a renewed interest in synchrotron theory. Synchrotron radiation was an irritant in early electron synchrotrons and storage rings. But it was soon realized that synchrotron radiation was a very valuable product in itself for research applications requiring intense and bright sources of light over a wide range of wavelengths. Electrons loose a large amount of energy in the form of synchrotron radiation putting a limit on the maximum attainable energy in a given type of accelerator. Let us first consider the case of the betatron. The betatron is a cyclic electron accelerator with a circular orbit of approximately constant radius which provides acceleration through *magnetic induction.* As the beam energy rises synchrotron radiation losses rise and begin to compete with the energy gained due to magnetic induction. In practice, the synchrotron radiation begins to become important at about $100 MeV$ and limits beam energies to about $300 MeV$. This challenge of the synchrotron radiation stimulated the development of accelerator technology and further increased the energy of the accelerated particles.

Here, it would be relevant and interesting to mention the very *exceptional* case of the charged-particles under uniform acceleration, *i.e.,* a constant force. This constant force can be produced, for example, by a constant uniform electrostatic field. From the special theory of relativity we know that a particle under a constant force executes hyperbolic motion. Does a charged-particle under uniform acceleration (hyperbolic motion) radiate? The answer to this question is not yet completely resolved! This topic is listed as one of the several *surprises in theoretical physics* in the compilation due to Peierls [2].

One of the characteristics of the synchrotron radiation is its intensity (energy emitted per unit time). Let us first consider the motion of a charged-particle of rest mass m_0 and charge q in a uniform magnetic field of strength B with the simplification that there is no component of the velocity along the field direction. We further decide to neglect the changes in the trajectory due to the radiation losses. In such a configuration the particle moves in a circle. The radius R of this circle is given by the well-known relation

$$R = \beta\gamma \frac{m_0 c}{qB} = \frac{\beta}{c}\frac{E}{qB} \tag{1}$$

where the total energy $E = \gamma m_0 c^2$, c is the velocity of light, $\beta = v/c$ and the relativistic factor $\gamma = \frac{1}{\sqrt{1-\beta^2}}$. In 1898 Liénard derived the expression for the total radiation intensity P for a charged-particle moving in circular motion [3]

$$P = \frac{2}{3}\frac{q^2 c}{4\pi\epsilon_0 R^2}\beta^4\left(\frac{E}{m_0 c^2}\right)^4 \tag{2}$$

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The radiated power depends on the rest mass of the radiating particle like $1/m_0^4$. For protons and electrons of the same total energy E the ratio of the radiated powers is

$$\frac{P_p}{P_e} = \left(\frac{m_e}{m_p}\right)^4 = 8.80 \times 10^{-14} \tag{3}$$

Synchrotron radiation is the dominant factor in the design of high energy electron synchrotrons and is an obstacle to exceeding $100 GeV$ or so in this type of accelerator. Only now synchrotron radiation is becoming a design consideration for proton synchrotrons. In the proton case, single-particle motion, to a very good approximation, exemplifies a Hamiltonian system. Particle motion in electron synchrotrons, on the other hand, is inherently dissipative.

II. QUANTUM EFFECTS IN SYNCHROTRON RADIATION

Synchrotron radiation was experimentally observed in a period when there was a very keen interest in analyzing the quantum corrections to the prescriptions based on the classical theories. The need of such studies also arose from the desire to achieve higher beam energies with the evolving accelerator technology. A quantum mechanical expression for the radiation intensity was derived by Schwinger [4] which is:

$$P^{\text{Quantum}} = P^{\text{Classical}} \left(1 - \frac{55}{8\sqrt{3}} \frac{\epsilon}{E} + \cdots \right) \tag{4}$$

where the critical energy of the radiated photon $\epsilon = \hbar\omega_c = \frac{3}{2}\gamma^3 \frac{\hbar c}{R}$. For an electron the quantum contributions become effective only at about $10^4 GeV$. There have been also studies to assess the effect of spin and the anomalous magnetic moment on the radiation intensity. These effects are also noticeable only at very high energies. As far as the radiation intensity is concerned the quantum contributions are of no consequence in any realizable accelerator. However, there are several other ways by which quantum effects manifest at energies realizable in many of the accelerators. The *quantum radiation fluctuations* start having an appreciable effect on the motion of the particles at energies exceeding $E_c = m_0 c^2 \left(\frac{m_0 c R}{\hbar}\right)^{1/5}$ which for an electron is about $500 MeV$ [5]. Quantum fluctuations of the radiation have to be taken into account in the engineering calculations of the particle motion. In passing it is to be noted that the quantum corrections to the *beam optics* are related to the powers of the de Broglie wavelength of the charged-particle. Hence the quantum corrections to the beam optics are more noticeable at lower energies [6]. One practical aplication of the *quantum formalism of charged-particle beam optics* would be to get a deeper understanding of the polarized beams.

It has been confirmed that the synchrotron radiation is responsible for the directional orientation of the particle spin *i.e.,* it leads to *radiation self-polarization* of the beam. As a result of the quantum fluctuations of the synchrotron radiation, the particle spin achieves a state whose orientation direction is opposite to that of the magnetic field. The particle beam becomes 92% polarized in a time τ given by

$$\frac{1}{\tau} = \frac{5\sqrt{3}}{8} \frac{\hbar}{m_0 c R} \gamma^5 \frac{q^2}{4\pi\epsilon_0 m_0 c R^2} \, . \tag{5}$$

For many realizable accelerators this time turns out to be about few hours and hence it is possible to observe (and utilize) radiation self-polarization in numerous storage rings. The radiation self-polarization is currently the only method of obtaining relativistic beams with an oriented spin. A novel proposal to produce polarized beams using the proposed spin-splitter devices based on the Stern-Gerlach kicks has been presented recently [7]. Polarized beams are very essential for many of the experiments in particle physics.

Some of the many important properties of the synchrotron radiation are summarized below:

1. The angular distribution of the synchrotron radiation is very sharply peaked in the direction of the particle's velocity vector within an angular width of $1/\gamma$. The radiation is plane-polarized on the plane of the particle's orbit, and elliptically-polarized outside this plane.

2. The radiation spans a continuous spectrum. The power spectrum produced by a high energy particle extends to a critical frequency $\omega_c = \frac{3}{2}\gamma^3\omega_R$ where the cyclotron frequency $\omega_R = \frac{c}{R} = \frac{qB}{\gamma m_0}$

These results imply that the synchrotron radiation is extremely intense over a broad range of wavelengths from the infrared through the visible and ultraviolet range and into the vacuum ultraviolet and soft and hard X-rays parts of the electromagnetic spectrum. The high intensity over a very broad spectrum range and certain other properties (including, collimation, polarization, pulsed-time structure, partial coherence, high-vacuum environment, ...) make synchrotron radiation a very powerful tool for a variety of applications in basic and applied research and technology. It is particularly important in those parts of the electromagnetic spectrum where laser sources are (presently) not available such as the vacuum ultraviolet, soft and hard X-rays, parts of the infrared, *etc.,*. The applications of the synchrotron light span a wide range of domains in fundamental science (chemistry, physics, biology, molecular medicine, *etc.,*) applied research (materials science, medical imaging, pharmaceutical R & D, advanced radiology, *etc.,*) and industrial technology (micro-fabrication, micro-analysis, photo-chemistry, *etc.,*).

III. NUMERICAL ESTIMATES

Using Equation (2) let us estimate the energy radiated by a single particle in one revolution. The time, T of one revolution is $2\pi R/\beta c$ and the energy $\mathcal{E}$ lost is

$$\begin{aligned} \mathcal{E} &= P \times T \\ &= \frac{1}{3}\frac{q^2}{\epsilon_0 R}\beta^3\gamma^4 \,. \end{aligned} \tag{6}$$

The maximum energy a particle can loose by radiation is all its kinetic energy, $K = (\gamma - 1)m_0c^2$. This can happen only at ultrarelativistic energies ($\gamma \gg 1$ and $\beta \approx 1$). The required γ is found by equating $\mathcal{E}$ to K. Then one gets

$$\gamma = \frac{1}{\beta}\left[3m_0c^2\frac{\epsilon_0 R}{q^2}\right]^{\frac{1}{3}} \,. \tag{7}$$

In the particular cases of an electron and a proton one gets

$$\begin{aligned} K_e &= 20R^{\frac{1}{3}}GeV \,, \\ K_p &= 5 \times 10^5 R^{\frac{1}{3}}GeV \,, \end{aligned} \tag{8}$$

where R is in *meters*. In any realizable accelerator R is about several km which limits the energy to several 100's GeV for an electron-synchrotron and to about a thousand TeV for a proton-synchrotron. So one needs to explore other types of machines. For high-energy e^+e^- colliders, *linear accelerators* become a very attractive option. This is why all $p\bar{p}$ colliders are circular and all future high-energy e^+e^- colliders will likely be linear. In the high-energy machines several *megawatts* of power is dissipated in the form of synchrotron radiation around the ring. This power loss is comparable to the power requirements of a small town.

IV. SYNCHROTRON FACILITIES

A synchrotron radiation facility is based on the technology of charged-particle accelerators. Bunches of charged-particles (usually, electrons) are made to circulate for several hours inside a ring-shaped, long tube under high vacuum. These rings have several beam lines with experimental stations and serve several sets of users simultaneously. Contrary to the expectation there are not very many synchrotron facilities to meet the huge demands of numerous users. This is due to the high costs (about a hundred million US $) and the required optimum technological expertise. Currently, around the world there are about fifty storage rings in operation as synchrotron radiation sources, located in twenty-three countries. About a dozen are under construction and another dozen or so are being planned. In Asia there are about twenty synchrotrons laboratories in nine countries: Armenia, China, India, Japan, Jordan, Korea, Singapore, Taiwan and Thailand. This small list leaves out not only many countries but the regions (such as the Continents of Africa and Australia) without a single synchrotron facility. India has the expertise and the experience of indigenously building two synchrotrons at the Centre of Advanced Technology (**CAT**) in Indore. **Indus-I** is a $450MeV$ synchrotron and **Indus-II** is a very energetic $2.0GeV$ synchrotron.

Storage rings are very flexible devices. By reusing most of the major components their performance can be upgraded at an incremental cost that is small as compared with the cost of construction of a new synchrotron. In recent years this flexibility is being innovatively exploited to relocate the very generously donated synchrotrons to those locations which are under-represented in the *World Synchrotron Map* [8].

V. THE MOST POWERFUL SYNCHROTRONS

The 8.0GeV **SPring-8** synchrotron is the largest synchrotron radiation source in the world and was completed in 1997 in Hyogo prefecture of Japan. Japan is one of the leading countries along with the United States and the European Union in accelerator-based science research. The SPring-8 belongs to the category of hard X-rays machines, along with the 7.0GeV Advanced Photon Source (**APS**) in Argonne, USA and the 6.0GeV European Synchrotron Radiation Facility (**ESRF**) in Grenoble, France. Owing to their extremely high energy these synchrotrons have their specific problems, and have forced the development of new techniques and new devices in the field of optics and detectors to ensure the required high stability of the electron beam. In view of the very unique challenges arising due to the very high energy the three most powerful synchrotron laboratories have signed a *Framework of Agreement for Collaboration* [9].

VI. ACCELERATOR PROGRAMMES IN INDIA

The accelerator programmes in India have a very long history. It had an early beginning in 1940 when Prof. Meghnad Saha developed a 37$inch$ cyclotron at the Calcutta based Institute of Nuclear Physics, which is now called Saha Institute of Nuclear Physics (**SINP**). In 1950, a 1.0MeV cyclotron was commissioned at the Tata Institute of Fundamental Research (**TIFR**) in Mumbai. In 1960, a 5.5MeV Van-de-Graff accelerator was installed at the Bhabha Atomic Research Centre (**BARC**) in Mumbai. In 1978, an indigenously designed and built 224cm diameter Variable Energy Cyclotron was made operational at the Variable Energy Cyclotron Centre (**VECC**) in Calcutta. Now, there are several Pelletrons such as the 6.0MeV Pelletron at the Institute of Physics (**IOP**) in Bhubaneshwar and the 14.0MeV Pelletron at TIFR. The Nuclear Science Centre (**NSC**) in New Delhi has a very energetic 150MeV Pelletron, which can accelerate very heavy ions to high energies. Very recently a beam of the radioactive isotope beryllium-7 was produced at the NSC. This marks India's entry into an elite group of nations which are doing research with radioactive-ion beams [10]. India has the expertise and the experience of indigenously building the two synchrotrons at the Centre of Advanced Technology (**CAT**) in Indore. **Indus-I** is a 450MeV machine and **Indus-II** is a very energetic 2.0GeV machine [11].

VII. ACCELERATOR MEETINGS IN INDIA

India, one of the very few countries which very regularly holds Accelerator and Beam Physics Meetings. For several years the Centre for Advanced Technology (**CAT**) at Indore has been holding a series of Schools on the *Physics of Beams* every year in December–January. This series of Schools is funded by the Department of Science and Technology (**DST**), with the aim of dissemination more widely in India, knowledge of, and interest in, beam physics. The School attracts several speakers from the premiere accelerator laboratories around the world. The Schools are very well-structured with tutorials and a few laboratory experiments. The participants of the School are further attracted to the *Summer Research Programme* conducted at CAT (see the very detailed School Reports in Ref. [12]). For over a decade the IUC-DAEF Calcutta Centre has been holding the tri-annual *National Seminars on Physics and Technology of Particle Accelerators and their Applications*. This series of National Seminars known by the acronym **PATPAA** provide a forum where all the accelerator physicists and technical personnel can meet and exchange their ideas and new developments. These PATPAA conferences, conducted once in three three years, attract a large participation from across the entire nation and some from abroad with enthusiasm and interest [13].

The above Schools are extremely significant since, the *Accelerator & Beam Physics and associated technologies* are **not yet** part of the regular university curriculum in most parts of the world! The learning of such an important interdisciplinary science is done to a very large extent individually and through the very few Schools *when and where* available [14]. We need to include accelerator & beam physics in the regular university curriculum. In passing it is to be noted that, there is **yet** to be an **Accelerator & Beam Physics Association/Society of India**. The **Japanese Beam Physics Club** [15] and the **Particle Accelerator Society of China** [16] provide the required Forums in their respective countries. When created, such an Association/Society will provide the much awaited Forum [14], strengthening the accelerator & beam physics community nation-wide. This has been the case in various other areas of Physics, for a very long time. Then, why should accelerator & beam physics continue to make an exception?

VIII. THE RELOCATED SYNCHROTRONS

Siam Photon Source: Recently the Japanese donated a $1.0 GeV$ synchrotron to Thailand [17]. Thus, Asia-Pacific region became the birth-place for the *Era of the Relocated Synchrotrons*. Located $250 km$ northeast of Bangkok in the city of Nakhon Ratchasima, the "Siam Photon Source" is Thailand's first synchrotron light facility and is intended to serve scientists throughout Southeast Asia. The original synchrotron light source, called SORTEC, was located in Tsukuba Science City, near KEK, Japan's High Energy Accelerator Research Organization. Thailand's Ministry of Science, Technology, and Environment got the machine *gratis* and is investing about US $ 15 million to move and upgrade it. This includes the doubling of the circumference to $81 m$ and tailoring the machine to produce narrow bright beams of soft X-rays and ultraviolet radiation. Scientists from the KEK have helped in the redesign and are training the scientists from Thailand to operate their new facility. Professor Tokehiko Ishii, the retired Director of the Synchrotron Radiation Laboratory at University of Tokyo is the key figure in orchestrating the donation. He is also overseeing the technical and scientific aspects of the transfer and upgrading of the synchrotron. The plan is to use the Siam Photon Source for physics and chemistry research, with some industrial research in semiconductors, medicine, pharmaceuticals, and agriculture. Siam Photon Source is scheduled to go on-line in 2001 [18].

SESAME: Jordan is the *first* country from the Middle East to join the elite group of countries possessing a synchrotron light source [19]. This became possible as Germany decided to generously gift the BESSY-I, a $800 MeV$ synchrotron, fully functioning since 1982 in Berlin, to the region of Middle East. BESSY stands for *Berliner Elektronen-Spiecherring für Synchrotronstrahlung*. BESSY-I is to be replaced by the more powerful BESSY-II, a $1.9 GeV$ synchrotron located in another part of Berlin. Germans are well-known for their environmentally responsible attitude towards reusing and recycling, and now they have very successfully extended that attitude to the large-scale research facilities! The idea of donating the BESSY-I Synchrotron came from Herman Winick of the Stanford Linear Accelerator Center (SLAC) in California, a member of the Machine Advisory Committee of BESSY-II, and the fellow committee member Gustav-Adolf Voss, a former director of Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Germany. The Project is known by the acronym **SESAME** (Synchrotron-light for Experimental Science and Applications in the Middle East) [20]. The SESAME Project reached a major milestone with the selection of a site in Jordan at a Meeting of the SESAME Interim Council in Amman, Jordan during 21-22 June 2000. SESAME will be the upgraded reincarnation of BESSY-I. The upcoming joint synchrotron radiation facility, which would be the first regional centre for cooperation in basic research in the Middle East will also serve as a seed for an International Centre built around the facility. SESAME will be located at the Al-Balqa' Applied University in Al-Salt and will be open to scientists from any country in the region or elsewhere. Because of this openness, organizers see its potential as not only a world-class research centre, but also as a politically important example of scientific cooperation in the region. Such a centre has been long overdue and it shall be the first of its kind in the region. The Centre will be operated and supported by its eleven member countries (Armenia, Cyprus, Egypt, Greece, Iran, Israel, Jordan, Morocco, Oman, Palestine and Turkey) with support from countries including, France, Germany, Italy, Japan, Russia, Sweden, Switzerland and USA. Other countries which have expressed an interest to join this new fount of science and medium of international cooperation include, Bahrain, Tunisia and Yemen. It is hoped that the new centre will be able to mirror the CERN in stimulating regional research collaboration. Very much like CERN, SESAME is under the very valuable political umbrella of UNESCO and is expected to promote science and foster international cooperation [21]. A broad-spectrum of planned research programmes include, structural molecular biology, molecular environmental science, surface and interface science, micro-electromechanical devices, X-ray imaging, archaeological microanalysis, materials characterization, and medical applications. A detailed account of events leading to the SESAME are available in [22,23].

DELSY: A Dutch accelerator and storage ring used for nuclear physics is being moved to Dubna, to add to Russia's Synchrotron capability [24]. The original facility, was located at the Institute of Nuclear Physics and High Energy Physics (NIKHEF) in Amsterdam, The Netherlands. This shall be the $1.2 GeV$ "Dubna Synchrotron Radiation Source (DELSY)", located at the Joint Institute of Nuclear Research (**JINR**) in Dubna.

IX. ASIAN COMMITTEE FOR FUTURE ACCELERATORS

The pace of development and the increasing role of accelerator-based science in Asia has led to the establishment of a forum, the *Asian Committee for Future Accelerators* (**ACFA**), to discuss and implement plans for further promoting collaborative accelerator-based science in Asia. The primary purpose of ACFA is to strengthen regional collaboration in accelerator-based science, to encourage future projects in Asia, and to make recommendations to governments. This organization was formed in 1996 and its members now include, China, India, Indonesia, Japan, Korea, Malaysia, Pakistan, Singapore, Taiwan, Thailand and Vietnam. The continent of Australia is also a member [25]. The First Asian Particle Accelerator Conference (APAC-1998) was held at the Japanese High Energy Accelerator Organization (**KEK**) under the auspices of the ACFA, stressing the importance of regional collaboration among Asian regions in the field of accelerator science and technology as well as accelerator-based science. The "Next APAC" is scheduled to be held during 17-21 September 2001 at Beijing, China [26]. Globally speaking, the International Committee for Future Accelerators (**ICFA**) [27], would provide an excellent framework for collaborations and forums. ACFA closely collaborates with ICFA, a longstanding organization of the world community. It is noteworthy to see how the ICFA Beam Dynamics Panel has contributed to the accelerator & beam physics. The well-attended and very regularly held ICFA Beam Dynamics Workshops are one of the proofs of its grand success.

X. CONCLUDING REMARKS

We have briefly discussed the synchrotron radiation and the synchrotron facilities, with a coverage to accelerator programmes in India. Siam, SESAME and DELSY are very unique facilities as they are being built by relocating the very generously donated synchrotrons. There are several countries which are in the process of building their own synchrotrons. Armenia is planning to build the $3.2 GeV$ **CANDLE**: *Center for the Advancement of Natural Discoveries using Light Emission* [28]. There is the proposal to build the $3.0 GeV$ **BOOMERANG** [29] under the *Australian Synchrotron Research Programme* (**ASRP**) [30]. Spain has the project for a $2.5 GeV$ *National Synchrotron Laboratory* (**LLS**) at Barcelona [31]. The upcoming synchrotron facilities will be able to bridge the gap in several of the under-represented regions of the *World Synchrotron Map* [8]. These, when built, will immensely benefit the scientific community in the concerned regions by enhancing international cooperation and providing them the latest technological expertise. Among the upcoming synchrotrons, SESAME is the most international project and offers an excellent opportunity for participation and active international collaboration. India could have participated and can still get involved and play a significant role [32].

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